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Project Summary

The research project described herein deals with the capability of training a human subject to control and/or interact with complex electronic or mechanical systems. Basically the project involves the detection of bioelectrical phenomena that are analogs of ongoing cognitive processes and the utilization of these phenomena to control external events. The project also allows the system being controlled to communicate with the human operator in either a feedback or an interactive manner. In bypassing the subject's manual or verbal response apparatus an appreciable time saving is achieved. By eliminating the normal feedback/interactive modes of communication currently employed by machines (generally visual signals produced mechanically or electronically) a further potential time saving is realized. However, the major advantage of the proposal is the virtually automatic control of systems operation by the trained subject.

To date we have trained a subject to respond to briefly displayed characters of the English alphabet using coded electromyographic responses.

Introduction

We are training subjects to respond to alpha-numeric symbols such that a discriminable response will be obtained to each symbol. The symbols are an abbreviated list of the English alphabet, and the digits zero through nine. The response is the electromyogram (EMG) recorded from the surface of the skin overlying muscle. The EMG is most directly an index of motor nerve activity rather than of muscle activity level since the magnitude of the electrical response is a direct function of the amount of neural activity imposed upon the individual motor units of skeletal muscle. The EMG is always present upon sufficient neural activity to elicit muscle movement and is also detectable given neural activity insufficient to generate movement. Interestingly, when a subject is instructed to "think about" flexing a specific muscle, a recording of the EMG accompanying this cognitive process is possible. In short, the EMG has the unusual property of being activated by the mere thought of activating the response system, e.g., the muscle (Leuba & Dunlap, 1951). This property of the EMG has been known for years (Hefferline & Perera, 1958) and has been utilized in several applied bioengineering situations, most notably the control of prosthetic devices. In this case the subject, with sufficient training, becomes quite adept at controlling his prosthetic device and reaches the point where he need not actively conceptualize a muscle movement to produce the EMG signals necessary to control the limb and reach his goal, but merely "thinks" of the desired movement to be performed. The thought of the movement is sufficient to produce the necessary EMG's. Later in his training he need not even think of the movements necessary to reach the goal, but merely thinks of the goal with the same lack of direct, conscious commands as does an intact human. It follows, of course, that the muscles used to control the limb cannot be occupied with other tasks that would produce error commands. This report will cover the progress made to date on the project.

Technique and Methods

The initial task was addressed to the problem of selecting EMG recording sites. The criteria used in selecting muscles to be used were as follows. The muscle must be superficial and not lie under an overly thick layer of adipose tissue which would act as an electrical shunt. The muscle had to be reasonably large such that a detectable EMG would be generated given minimal neuromuscular activation. Since our task will eventually require very rapid patterns of responses the muscle had to be capable of responding at high rates of brief contractions. We have limited ourselves to surface recording of the EMG with disc electrodes. This necessitated a recording site which was not affected by the activation of other muscles lying adjacent to our target muscle. Thus we were seeking a muscle which was relatively anatomically isolated. A prime consideration dealt with the possible confounding effects of using muscles which might be expected to be utilized in normal postural control. For this reason we eliminated most of the large muscles of the limbs (they also are incapable of responding at high frequencies). After trial we eliminated the muscles of the face and head because they were 1) too small and 2) were involved in largely involuntary movements associated with respiration, swallowing, eye blinks, etc. Since we want to utilize a rather subliminal muscular contraction a muscle with as high an innervation ratio as possible would be desirable. Finally, for practical reasons, the muscle had to be readily accessible without embarrassment or discomfort due to electrode placement.

Muscles that were considered and rejected for one or more of the above reasons included: frontal and occipital epicranius, orbicularis oculi, superior auricular, depressor labii inferioris, masseter, trapesius, biceps brachii, brachioradialis and other superficial muscles of the forearm. The muscles deemed most suitable for this project were the flexor pollicis brevis (flexion and adduction of thumb) and the abductor digiti minimi (abducts little finger) both intrinsic muscles of the palmar surface of the hand. To simplify the subject's task we have utilized four muscles giving 16 response combinations. From these 16 codes (15 codes plus zero) one can construct a communicable alphabet (see Appendix A).

Once chosen the muscles were mapped on the surface of the overlying skin to determine the location yeilding the best signal to noise level. Using differential amplification the most satisfactory results were obtained by placing the active electrode over the belly of the muscle and the indifferent over the distal tendon. All recording configurations employ ankle plate or earlobe grounding. Amplifier gain was from 30-150 μV/cm. (Grass polygraph--EEG channel) with a bandpass of 1 to 75 Hz. Figure 1 shows a recording from the flexor pollicis brevis (brevis) and abductor digiti minimi (minimi) for both hands. The subject here is performing low amplitude twitches of the muscles at will.

Testing and training took place in a sound-attenuating, ventilated chamber which was dimly lit (see Figure 2). The subjects sat in a comfortable, stuffed chair and were not required to utilize any of their musculature to remain in a comfortable position. The subject faced a window in the room through which they saw the lamp display and alphanumeric display devices (to be described later). A black cloth around these

units reduced distracting visual stimuli to a minimum. The EMG was recorded using gold disc electrodes and electrode paste and held on with tape. We are currently devising a glove-electrode assembly to facilitate placing of the electrodes in the same location on the muscle from one session to the next.

Preliminary Training

We noticed that although the two muscles on each hand are well separated that the contraction of one was accompanied by the activation of the other to a noticeable degree. Our first step was to eliminate this interaction. To this end we placed a 4-trace oscilloscope in front of the subject. The subject saw each EMG channel and received immediate visual feedback that served two functions. One, it effectively eliminated the muscle interactions by allowing the subject to observe and suppress the "wrong" response. Secondly, it gave the subject a "feel" for what kinds of bioelectric signals she could produce.

During this phase of training, the subject was instructed to twitch her muscles at will and simply observe the oscilloscopic display. The subject was asked to attempt to twitch each muscle independently and in various combinations. She was also asked to make smaller and smaller twitches. The subject found these tasks relatively easy. In fact at the end of this phase of training the subject was able to issue quite respectable potentials (about 50-100 μ V) without any apparent movement.

Patterned Light Training

In preliminary training the subject gained some control over individual muscles and learned to deliver threshold twitches. It was now necessary for the subject to learn to fire particular muscles in a coded manner. Each of the truncated list of English alphabet characters was assigned a particular code (see Appendix A). These codes can be considered as four lamps which can be lit or dark in various combinations. Thus to train the code to the subject we employed a lamp display panel (see Figure 3). The display consists of two rows of incandescent lamps. Lamps in the top row have orange lenses, the lamps or the bottom are green and the single lamps on the extreme right and left are red.

Rather than initially present the alphanumeric display and the associated code as displayed on the lamp display we first trained the subjects to respond correctly to the lamps alone. It was felt that this was a somewhat simpler task and that the alphanumeric display could be added later. The task consisted of the presentation of a pattern of lit lamps on the upper row. The upper row of lamps for convenience are referred to as the <u>S Code</u> (Stimulus Code) lamps. The subject was to turn on the lower row of lamps such the pattern of lit lamps in the two rows coincided. The lower row of lamps will be referred to as the <u>R Code</u> (Response Code) lamps. Thus the task is a match-to-sample paradigm.

Every 6-10 seconds the S Code is displayed for a variable period of time (from 3 sec down to 1 sec as training progresses). At the same time the left hand red lamp is lit signalling the start of a trial (termed the GO lamp). The subject then issues a response. If successful in matching to the sample the right hand red light is lit (reinforcement lamp). At the end of the trial the lamp display panel is turned off. During the intertrial interval (ITI) any responses from the subject are deemed errors. A response during the ITI lights the appropriate R Code lamp. These lamps are reset at the start of the succeeding trial. Since we do not want the subject to generate responses during the ITI we also provide auditory feedback to the subject at all times. Thus the subject not only sees the lamp lit he also hears the amplified EMG that resulted in the error. Presently the auditory feedback is the sum of the four EMG responses. We do not presently know the contribution of the auditory and visual feedback, or which is more effective, in our training procedure. We are presently designing an auditory feedback device which will convey more information to the subject regarding which muscle was activated.

The initial training was accomplished with logic devices as shown in Figure 4. The four channels of EMG information were amplified and simultaneously written onto a pen-writing polygraph. The amplified and filtered EMG was fed into a series of level detectors which produced standard logic level pulses when the voltage of the EMG exceeded a preset level. The output of the level detectors set R Code flip-flops which in turn activated lamp drivers providing a visual lamp display. The output of the R Code flip-flops in addition activated two interfaces; one to a chart recorder for a printed record of responses, the other to the computer external sense lines.

The S Code presented on any trial was randomly determined by a high-speed digital clock that transferred its count to the S Code flip-flops upon command from a timer. The flip-flops in turn activated the lamp drivers and S Code lamps of the display panel. The S Code, too, was routed to a chart recorder and the computer. The reinforcement lamp was lit when the output of the coincidence logic indicated that the R Code equalled the S Code. Twenty-five trials constituted a block and a session contained ten blocks. The subject attained 90 to 95% correct match-to-sample responses at 1 sec display time after 1000-1500 trials. Figure 5 presents a polygraph record of the subjects performance at the end of this phase of training. As can be seen the baseline is relatively quiet. Most of these responses occur in the absence of any overt twitch. The latency of the response varies between 150 and 200 msec.

Figure 6 presents the results of a session after the subject had mastered the match-to-sample task. In this particular session the subject was exposed to four different display times: 3.0, 2.5, 1.5 and 1 sec. Plotted are the percent correct responses per block for the various display times. As can be seen the longer display times represented a relatively easy task. At one second display times the subjects performance improved from 50% correct (where 6% is the chance level) to 85% correct in three blocks. Interestingly when the subject made an error there was often an increase in intertrial responses. This probably reflects an emotional response on the part of the subject to the cognizance of making

an error. At the end of this phase of training the subject evidenced a high degree of control over the EMG responses to the S Code lamps.

Alphabetic Training

The next phase of training involved the association of the S Code lamps with a particular alphanumeric display. Referring back to Block Schematic A (Figure 4) note that the S Code is relayed to the computer. The computer decodes the S Code and displays on the remote alphanumeric display the appropriate alphabetic character. In the early stages of this training the alphnumeric display and the S Code lites were presented simultaneously for a relatively long time (2-3 sec). The subject was instructed to learn the association between the S Code lamp patterns and the alphabetic character displayed. The codes are presented in Appendix A.

The subject learned the association in several sessions. The S Code lamps were then turned off leaving only the alphabetic character displayed. The R Code lamps, the GO lamp and the reinforcement lamp were still present. Figure 7 presents the results of a session of alphabetic display training only. In this session the characters were displayed for either 2.0 sec or 1.0 sec. It is apparent that the longer display is again an easier task. These data were also analyzed for a trials effect across blocks within the session (Figure 8). The 25 trials were collapsed into five blocks of five trials. The data are expressed for the 1.0 sec display time, the 2.0 sec display time, and for both display times pooled together. Across trials one can see that performance improved but that it falls off somewhat at the end of the block. This latter effect may reflect a fatigue phenomena which might be alleviated by either a longer inter-trial-interval or fewer trials in a block. In any event the subjects performance to the characters alone is quite good, at the time of this writing having reached about 80% correct for a 1 sec display.

A point of considerable interest and excitement is that the subject is reporting that occassionally (perhaps 10% of the time) the correct response is made without any "awareness" or "conscious control" on her part. In other words the subject is not voluntarily activating the appropriate muscles. Rather the correct responses appear, to use her term, "automatically." This is precisely the result we were seeking and are now devising techniques to maximize this automaticity. These techniques include shortening the display period even more to force the subject to not rely upon conscious commands to gain a reinforcement and overtraining to the alphabetic characters.

The control logic now in use leaves much to be desired in terms of reliability, flexibility, and convenience. We are currently rebuilding the control and analysis system to shift the job entirely to the computer. Block Schematic B (Figure 9) depicts the system configuration. The EMG R Code will be captured in the same manner as before but will then be routed to a series of comparators to perform an analog to digital conversion. The computer external sense lines will then decode the R Code and 1) activate the R Code lamps and/or 2) display the R Code alphabetic

character on the alphanumeric display. The S Code will be generated either by a random logic device or can be entered via the teletype (TTY). The computer will then present the S Code (either lamps or alphanumeric display) and monitor and display the R Code (either lamps or alphanumeric display) as well as signal a reinforcement. The R Codes and S Codes will be stored in digital mass storage for subsequent analysis. The reinforcement lamp will be lit given a correct response and will stay lit during the ITI unless an error is made. Thus the subject's task will be to keep the reinforcement lamp lit as much as possible. To facilitate this and provide an additional incentive a computer controlled clock will accumulate reinforcement times within blocks. The clock will be observable by the subject.

The next phases in the project include strengthening the response to the letter display both in terms of accuracy and speed. The subject will then be given the opportunity to, if you will, "spell" words using her EMG response. The words will be displayed on the alphanumeric display giving the subject immediate feedback. The subject will also be presented with simple words on the display. We will then train her to respond to the word by "spelling" the characters via the EMG in a manner consistant with computer decoding. We have been impressed with the facility with which our subject has been able to learn this task to date. We will also investigate the role of auditory and visual feedback in the learning of this task. Our impression is that these kinds of feedback are essential to facilitate rapid acquisition of this task. We plan upon replicating the procedures listed above on other subjects to ensure their reliability. This will also enable us to test various notions about the most effective training procedures.

References

Hefferline, R. F., & Perera, T. B. Proprioceptive discrimination of a covert operant without its observation by the subject. Science, 1963, 139, 834-835.

Leuba, C., & Dunlap, R. Conditioning imagery. J. exp. Psychol., 1951, 41, 352-355.

Appendix A

Below are the S Codes and their corresponding alphanumerics. The codes were devised with the following considerations in mind. First it was thought to be desirable to give the most commonly occurring alphabetic characters the simplest code. Thus the letter E received a simple code: the right brevis alone. Since we have 15 codes to issue we determined the 15 most frequent letters and tested them for intelligibility. The 15 letters below comprise a high percentage of those letters actually used in normal communication and can convey a good deal of information.

The codes are given octal representation merely as a convenience.

Alphabetic Character	Left Minimi 4	Left Brevis 3	Right Brevis 2	Right Minimi 1	Binary Code	Octal Code
E			X		0010	02
A		X			0100	04
I				X	0001	01
N	X				1000	10
O		X	X		0110	06
R	X	X			1100	14
S			X	X	0011	03
T	X			X	1001	11
L		X		X	0101	05
C	X		X		1010	12
U		X	X	X	0111	07
P	X		X	X	1011	13
M	X	X		X	1101	15
H	X	X	X		1110	16
D	X	X	X	X	1111	17

The Xs indicate which of the lamps are to be lit for a given alphabetic character.

Figure Legends

Figure 1 Polygraph recording of EMG's obtained from relatively untrained subject instructed to perform low amplitude twitches of four muscles at will. Minimi refers to the abductor digiti minimi (little finger); brevis refers to flexor pollicus brevis (thumb). Gain = 75 μV/cm; speed = 2.5 mm/sec.

Figure 2 Physical arrangement of the training facilities.

Figure 3 Representation of the interactive display devices. The subject is seated 1 meter in front of the window.

Figure 4 Block Schematic A. Logic devices utilized in initial training.

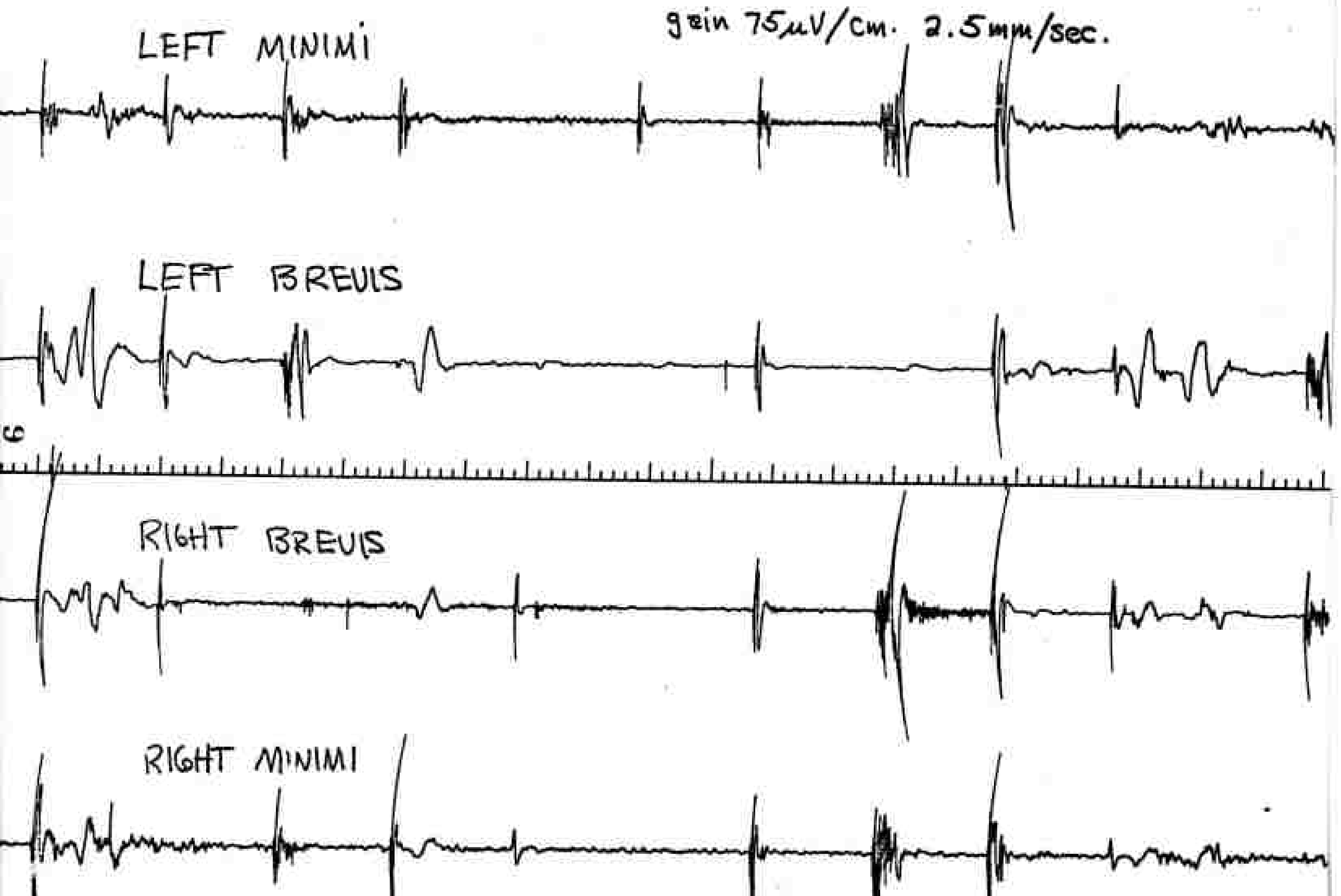
Figure 5 Polygraph recording of EMG's obtained from a subject well trained on the lamp display match-to-sample task. Gain = 50 μV/cm; speed = 5 mm/sec.

Figure 6 Results of a final session of lamp display match-to-sample training. Plotted are the percent correct responses per block of 25 trials as a function of display time.

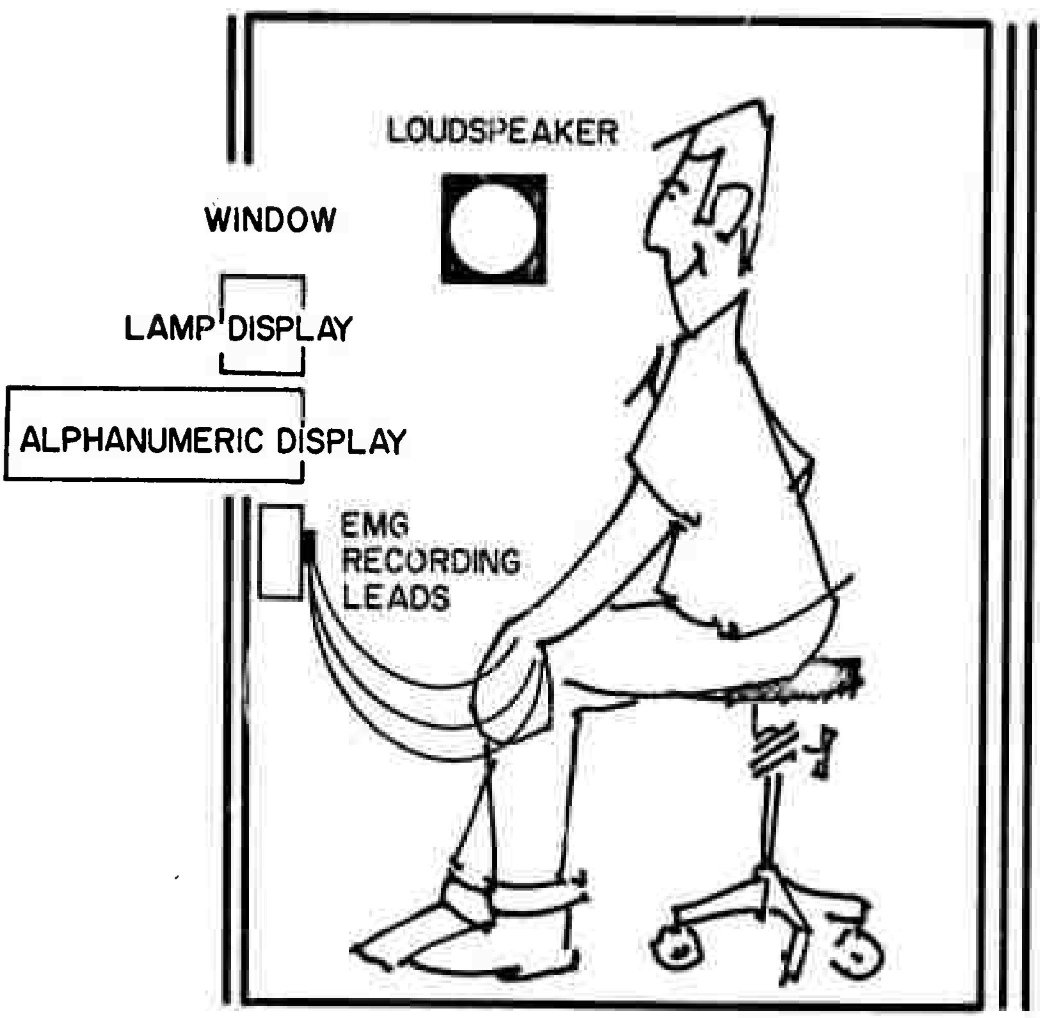
Figure 7 Results of a session of alphabetic display training. Plotted are the percent correct responses per block of 25 trials as a function of display time.

Figure 8 Results of the alphabetic display training analyzed for a trials effect across blocks within a session. The 25 trials were collapsed into 5 blocks of 5 trials each. Plotted are the percent correct responses per 5 trial block as a function of display time (1.0 sec display, 2.0 sec display, and both display times pooled together).

Figure 9 Block Schematic B. Systems configuration to support the experimental control and data analysis of the project.


gain 75µV/cm. 2.5mm/sec.
LEFT MINIMI
LEFT BREVIS
9
RIGHT BREVIS
RIGHT MINIMI

PHYSICAL ARRANGEMENT



SOUND ATTENUATING ROOM

2

INTERACTIVE DISPLAY DEVICES

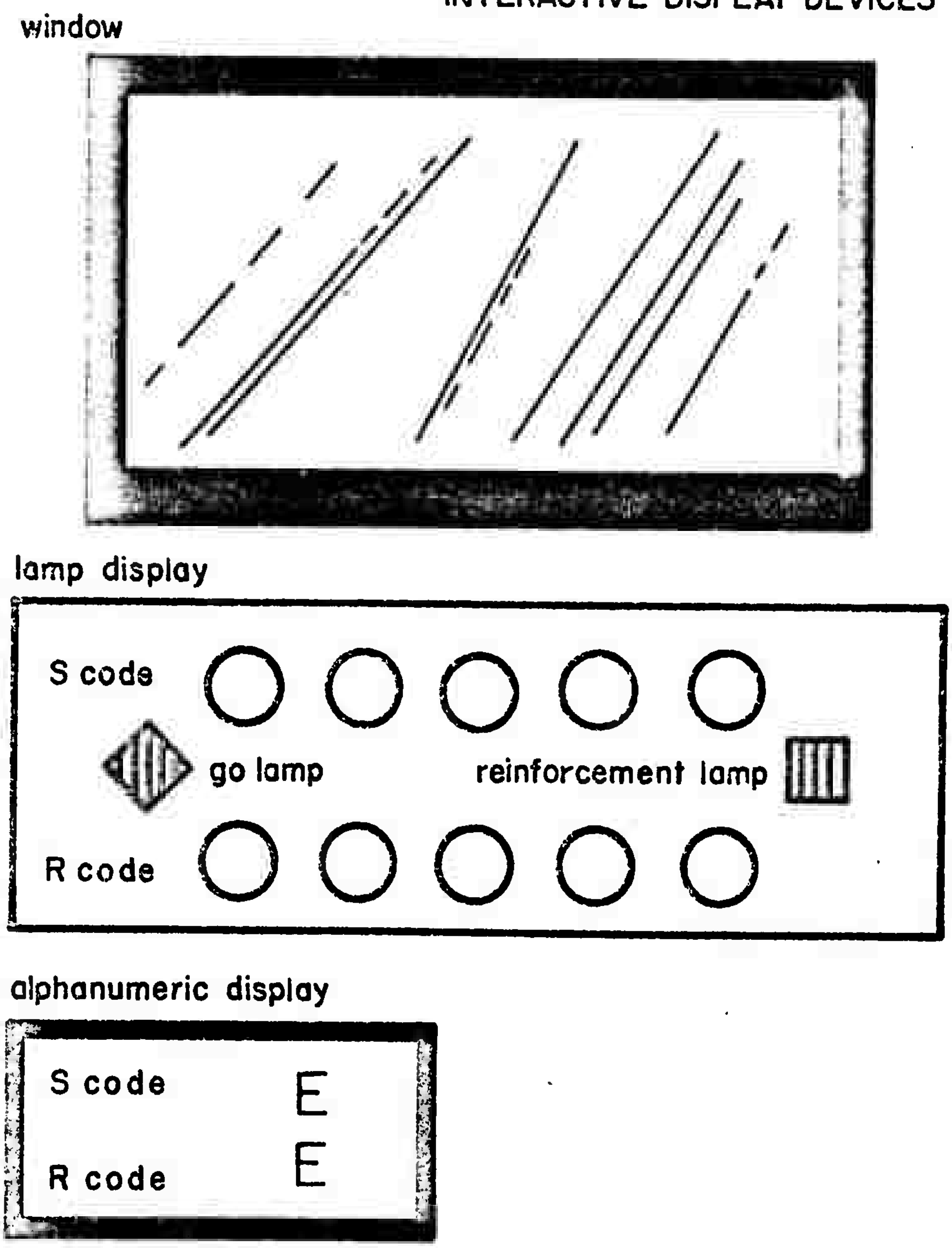
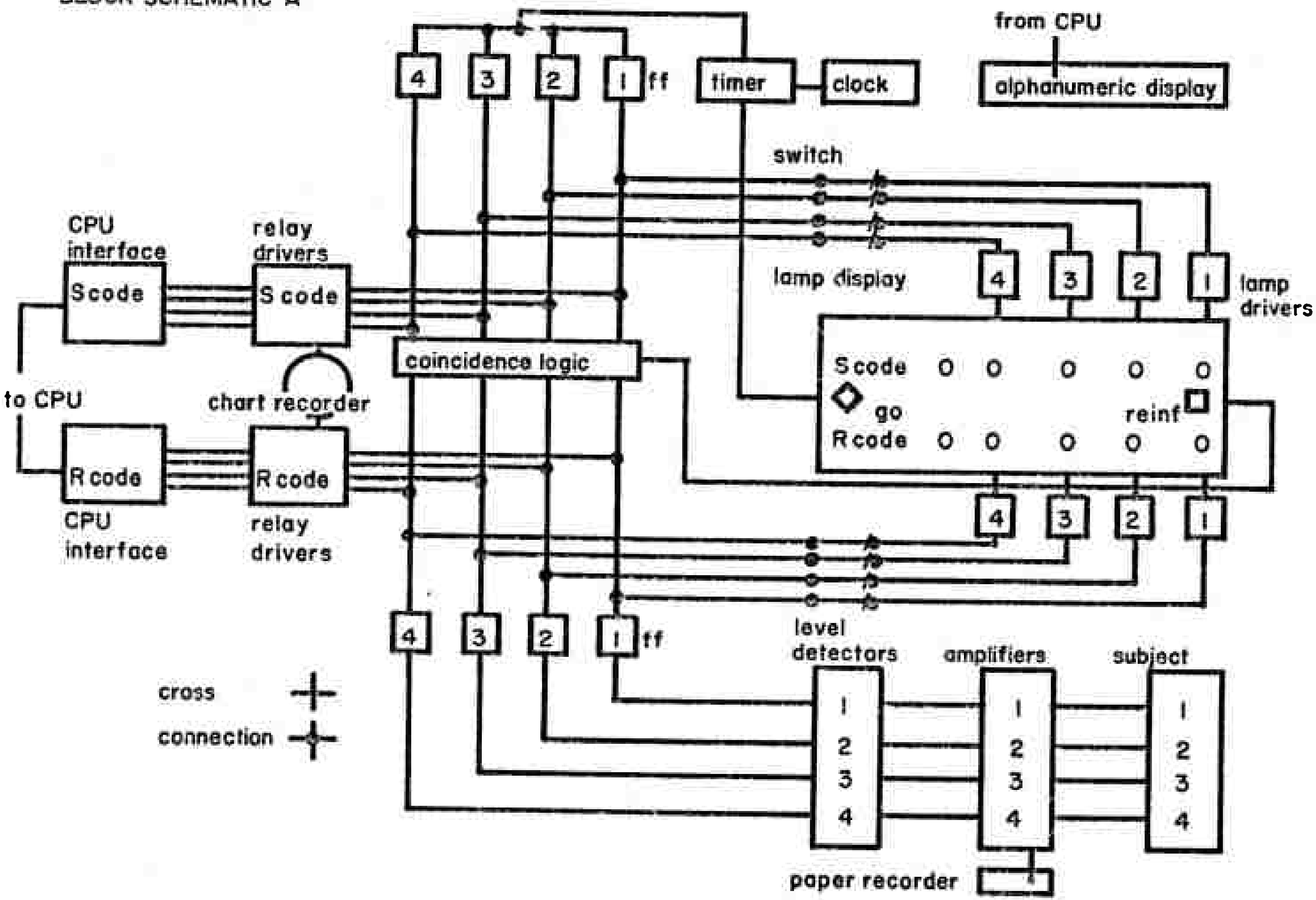
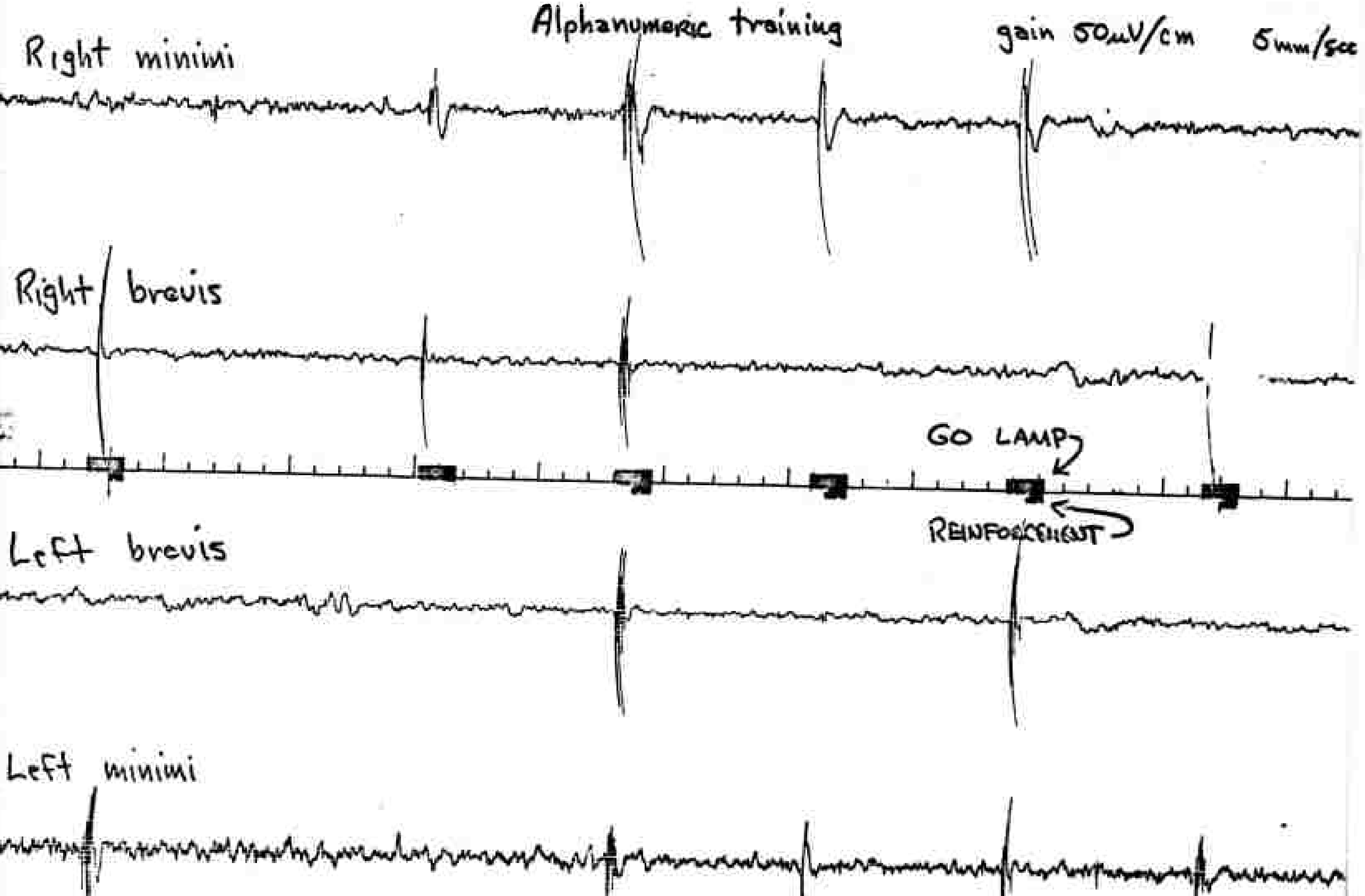


Fig. 3

BLOCK SCHEMATIC A





Alphanumeric training
gain 50µV/cm
5mm/sec
Right minimi
Right brevis
GO LAMP
REINFORCEMENT
Left brevis
Left minimi

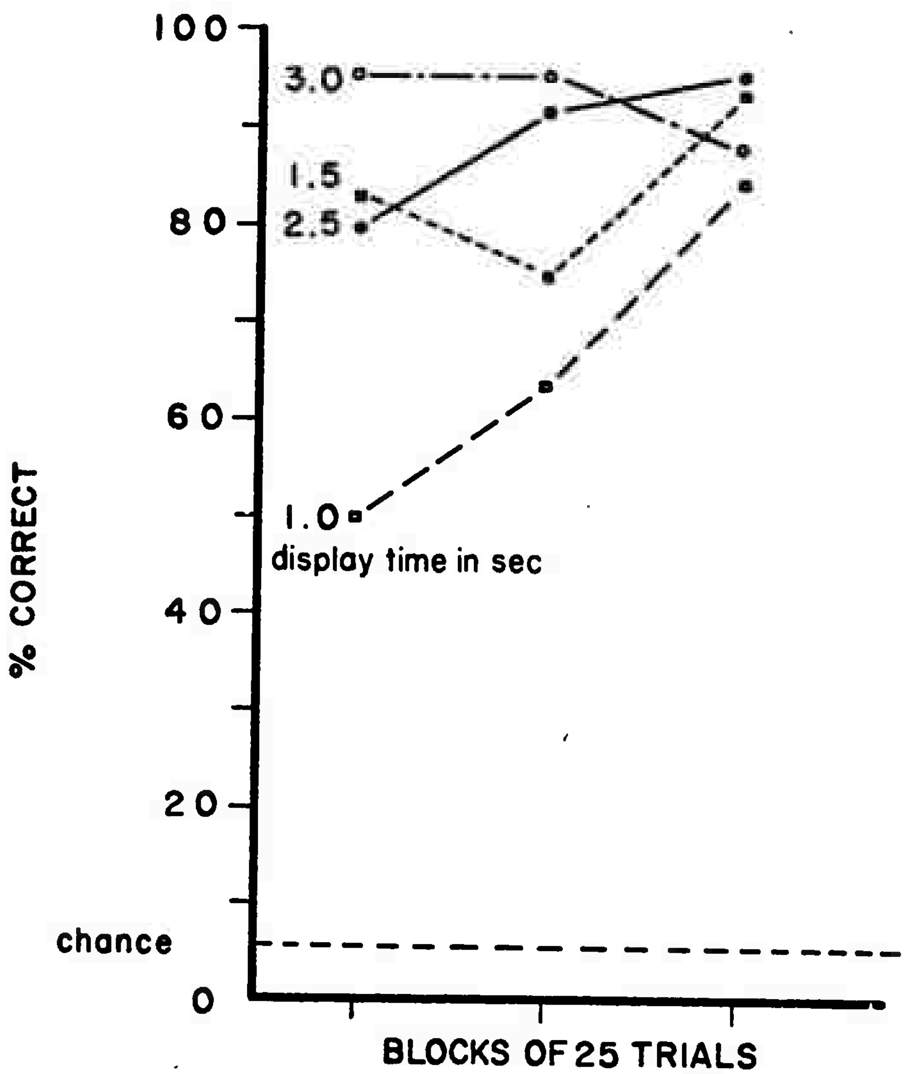
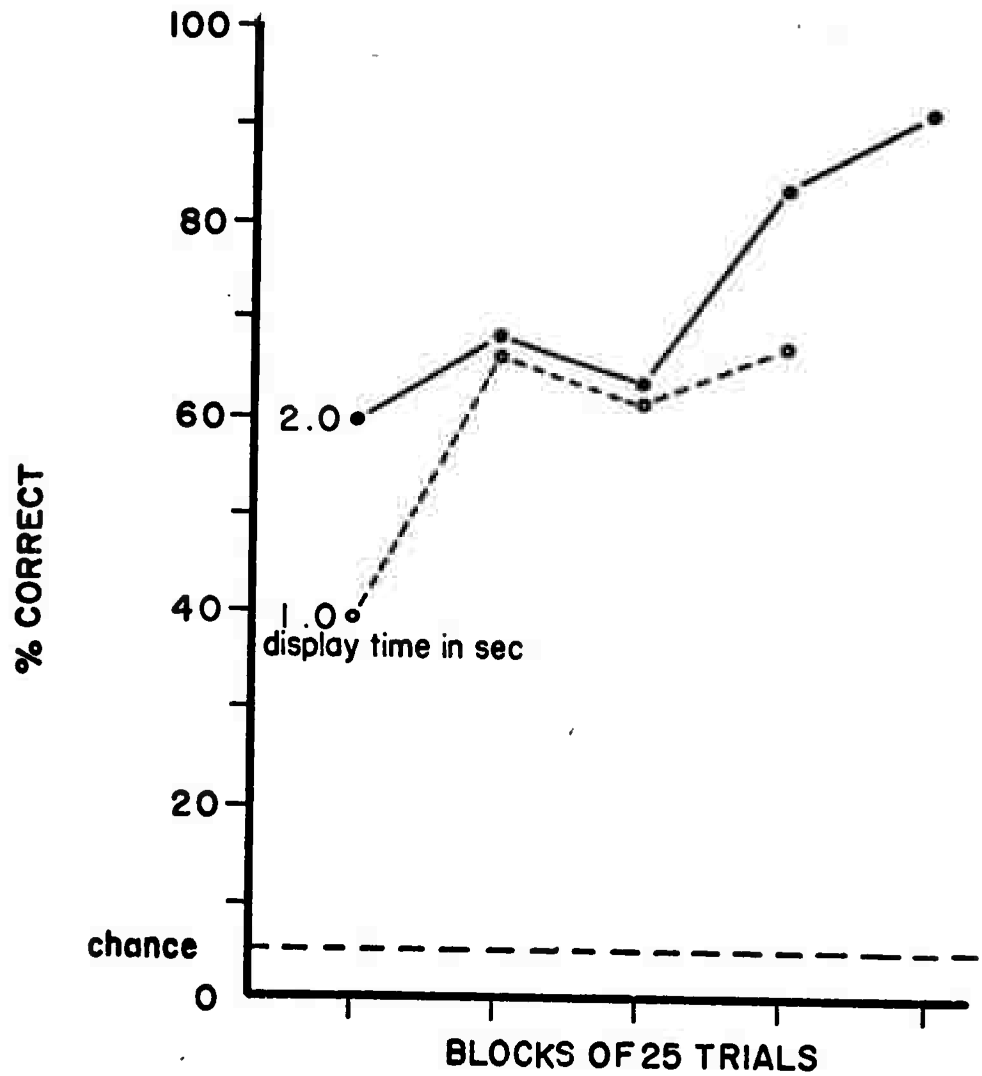
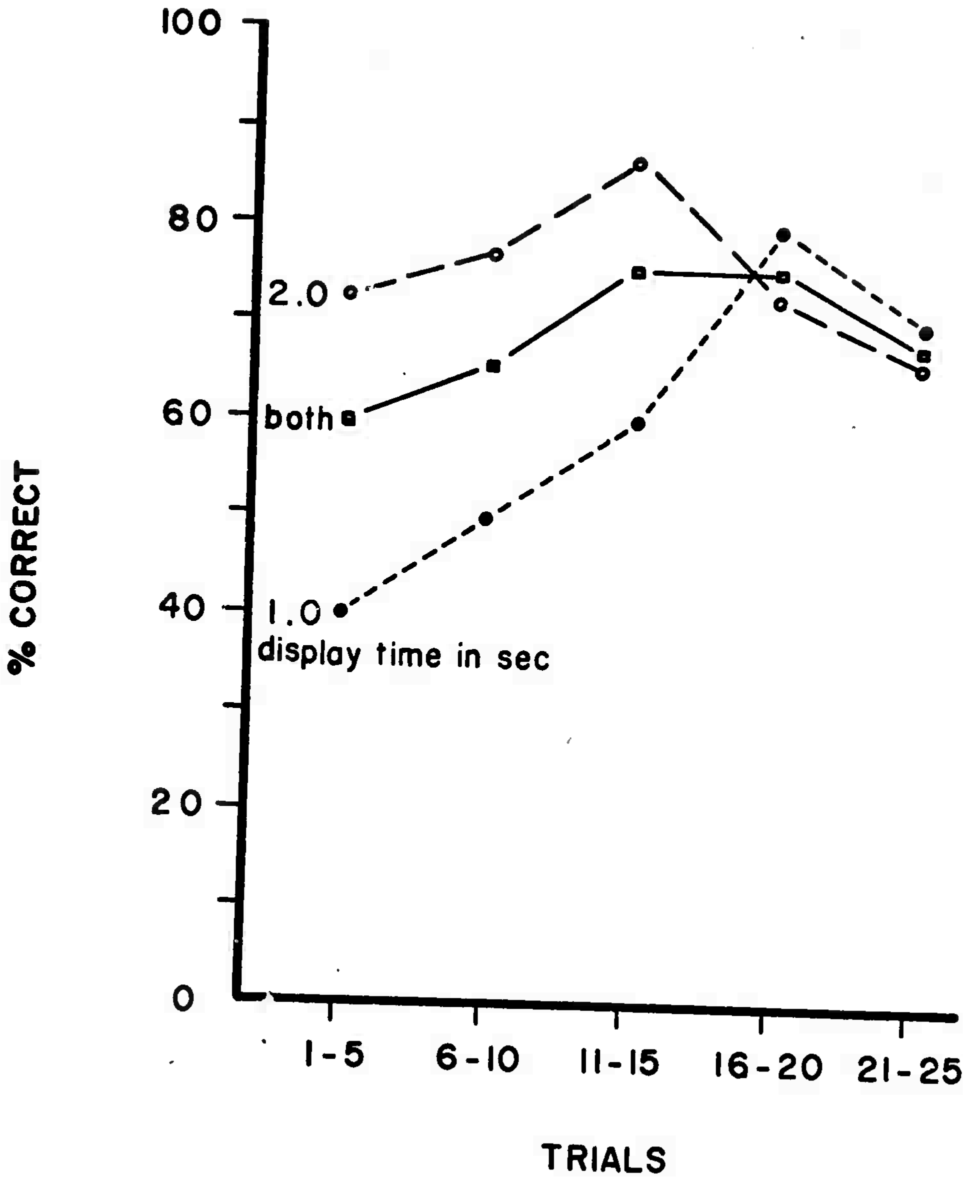

100
80
60
40
20
0
% CORRECT
3.0
1.5
2.5
1.0
display time in sec
chance
BLOCKS OF 25 TRIALS

Fig. 6



100
80
60
40
20
0
% CORRECT
2.0
1.0
display time in sec
chance
BLOCKS OF 25 TRIALS

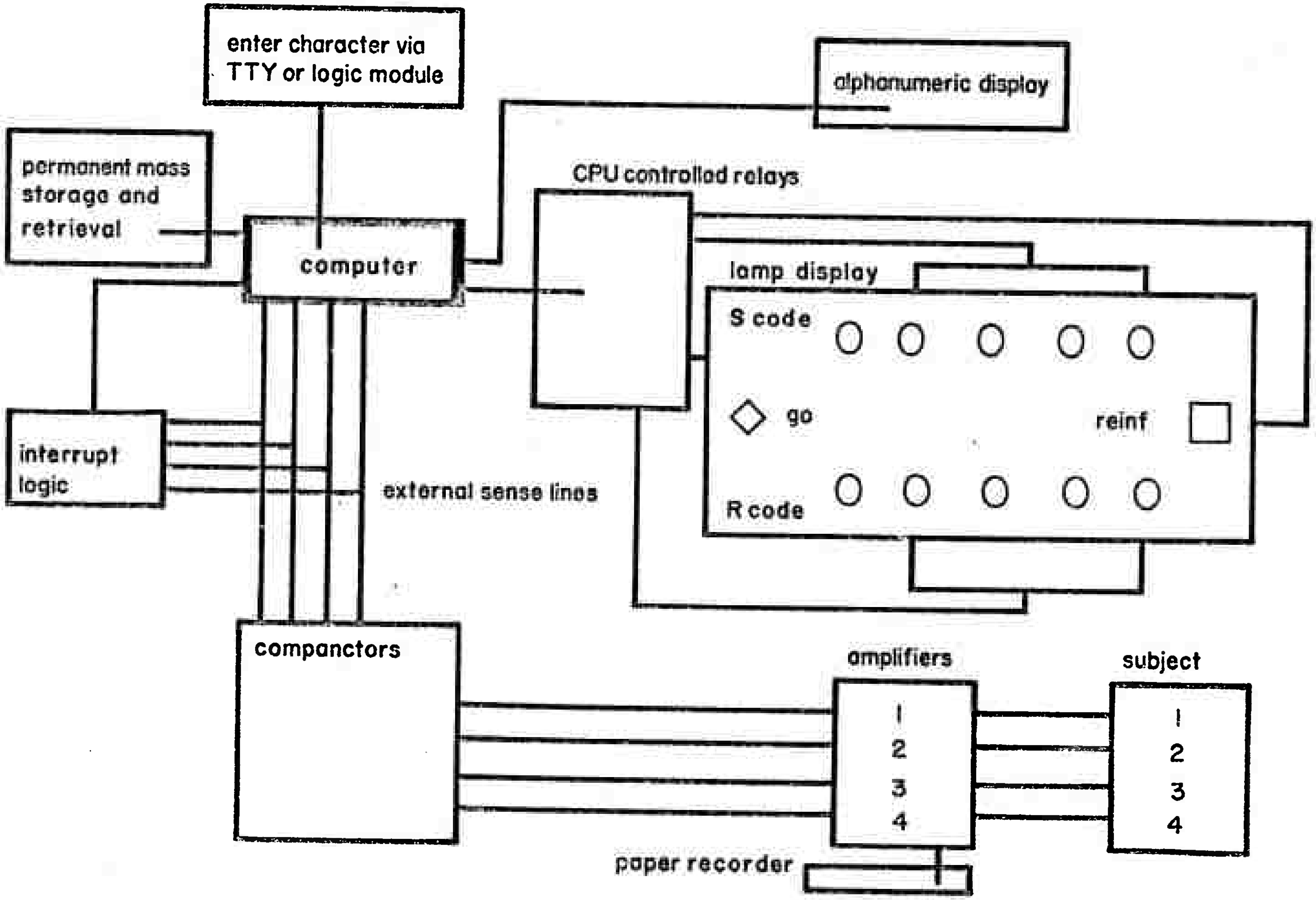
Fig. 7



100
80
60
40
20
0
% CORRECT
2.0
both
1.0
display time in sec
1-5
6-10
11-15
16-20
21-25
TRIALS

Fig. 8

BLOCK SCHEMATIC B



F. 9